

A NEW LOOK INTO THE SPECTRAL AND LIGHT VARIATIONS OF ϵ AUR

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Abstract. Investigating long series of spectral and photometric observations, we found that the orbital elements of ϵ Aur are subject to much larger uncertainties than usually believed. The $H\alpha$ emission is found to move basically with the F primary but its exact location should still be investigated. We also find strong additional absorption and large reddening of the object near the third contact during the eclipse. Episodic atmospheric mass transfer from the F primary towards its companion is tentatively suggested.

Key words: eclipsing binaries - spectroscopic binaries - variable stars - ϵ Aur

1. Observations

Having at our disposal rich series of spectral and photometric observations of ϵ Aur, we attempted to find out what are the safe and uncertain observational facts about this intriguing binary and provide also some speculations about its true nature. In particular, we analyze the following sets of spectra from the red spectral region covering $H\alpha$: 112 DAO CCD spectra from 1994 – 2011; 292 Ondřejov spectra from 2006 – 2012; and 15 Lisbon spectra from 2011 – 2012. Systematic *UBV* photometry, carefully calibrated to the standard Johnson system was obtained at Hvar and combined with the *BVRI* photometry secured by AH in the framework of the AAVSO program.

2. The timing of the last eclipse

All time instants in this paper are in RJD=HJD-2400000.0 (HJD being the heliocentric Julian date of observation). The photometric eclipse lasted from RJD 55050 to 55800; the epoch of the primary mid-eclipse being RJD 55403 (Chadima *et al.*, 2010), the second contact RJD 55225 and the third contact RJD 55620. The spectroscopic eclipse as seen in the $H\alpha$ absorption started, however, *three years earlier* (Chadima *et al.*, 2011).

3. What can be learned from the dynamical spectra?

We first investigated the dynamical spectra of three strongest unblended lines in the red spectral region. Figure 1 shows the evolution of the $H\alpha$ profile. Three facts are worth noting: 1. The appearance of additional $H\alpha$ absorption on the red and then blue side of the profile *is not symmetric* around the mid-eclipse. The blue-shifted absorption after the mid-eclipse is stronger and more extended than the red-shifted one prior to mid-eclipse. 2. The $H\alpha$ emission is completely masked by this extended absorption. 3. While the emission exhibits cyclic changes in the V/R ratio of the violet and red peaks, one can note that prior to eclipse, the V peak of the emission was statistically stronger than the R peak.

A comparison of the dynamical spectra of two strong metallic lines, Si II 6347 Å and Fe II 6417 Å (cf. Figure 3) reveals two interesting things: 1. While the general behavior of both lines shows similar patterns, one can note an extended blue-shifted absorption in phases near the third contact (RJD 55600) seen in the Fe II 6417 Å line only. The inspection of the spectra shows that there is actually a line doubling seen in Fe II 6417 Å. 2. In the course of the eclipse, one can see indications of some travelling subfeatures appearing in the blue wings of both lines and moving across the line profiles to the red, probably due to rotation of the medium responsible for the absorptions. A prototype of such variations is ϵ Per – (see Figs. 4 to 8 in Gies and Kullavanijaya, 1988).

4. Orbital and physical RV changes and the problem of true orbital elements

To investigate the effect of physical RV variations, which have an amplitude comparable to the orbital RV changes, local RVs at various relative intensity levels were measured in the clean profiles of Si II 6347 Å and Fe II 6417 Å

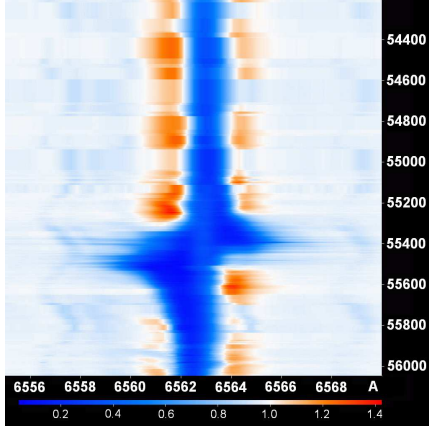


Figure 1: The dynamical spectra of the $H\alpha$ line profile over the time interval prior to, and during the recent eclipse. The sequence of events seems to be similar to that observed in $H\alpha$ by Wright and Kushwaha (1958).

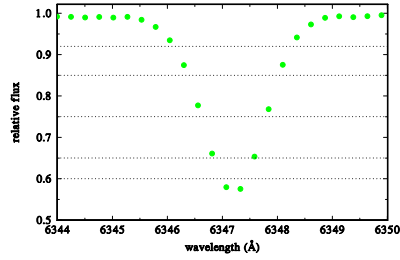


Figure 2: A line profile of Si II 6347 Å with relative intensity levels, at which the local RVs were measured, shown by dotted lines.

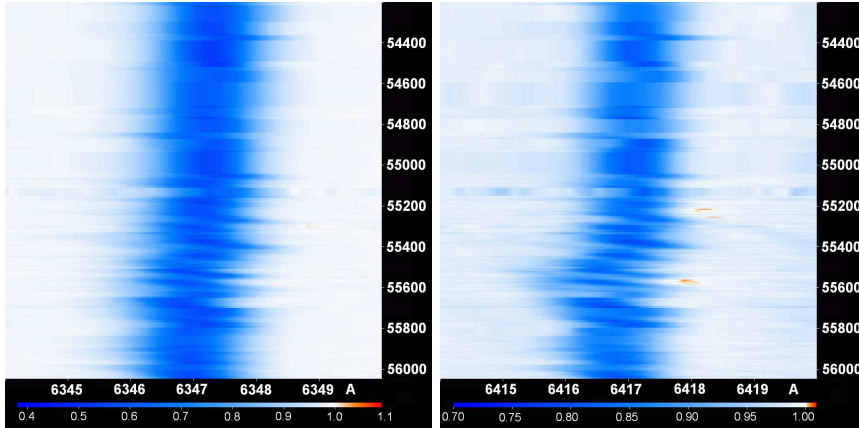


Figure 3: The dynamical spectra of the Si II 6347 Å (left) and Fe II 6417 Å (right) line profiles over the time interval prior to, and during the recent eclipse.

Table I: Orbital elements of ε Aur based on the RVs of the wings of H α emission and on the RVs of weak symmetric absorption lines. The orbital period was kept fixed at 9890^d26 (Chadima *et al.*, 2010).

Element	H α emission wings	weak symmetric absorptions
$T_{\text{min.I}}$ (RJD)	55526 \pm 383	55389 \pm 173
$T_{\text{min.II}}$ (RJD)	61485	61194
e	0.167 \pm 0.033	0.301 \pm 0.038
ω (deg.)	15 \pm 15	64.1 \pm 8.1
K_1 (km s ⁻¹)	9.1 \pm 1.2	13.28 \pm 0.95
γ (km s ⁻¹)	-1.60 \pm 0.34	-2.26 \pm 0.56
rms 1 obs. (km s ⁻¹)	3.55	5.67

lines (cf. Figure 2). The choice of levels was dictated by the limited resolution 11700 of the Ondřejov spectra.

First, we derived the bisector RVs at various intensity levels for both lines, averaging the local RVs from the blue and red wing measured at the same level. Then, the orbital solutions were derived with the program FOTEL (Hadrava, 2004a) for the bisector RVs measured at various levels of the profiles. The results, shown graphically in Figure 4 indicate that all orbital elements may vary systematically (though the associated errors are not negligible) over a wide range depending on the depth within the line profiles where the bisector RV was measured! In particular, the predicted epoch of the mid-eclipse agrees well with the observed one (RJD 55400) only for RVs derived on the outer wings of the profiles. Also the semiamplitude, eccentricity and orientation of the orbit vary quite substantially. This may have important consequences. First, since the orientation of the orbit is *poorly constrained*, one should look for the secondary minimum in the far IR systematically and without prejudice, it might come already some 15 years after the primary mid-eclipse! Its firm detection would help to constrain the true orientation of the orbit. Note also that the difference between $K_1 = 9.1$ km s⁻¹ (Table I) and 14.8 km s⁻¹ (Figure 4) is huge for the long orbital period of ε Aur: For instance, for a primary mass of 20 M $_{\odot}$, the corresponding range of mass ratios following from the mass function is 0.42 to 0.77, implying the secondary mass between 8.4 and 15.3 M $_{\odot}$.

We also derived RV curve of the H α emission wings and of weak symmetric absorption lines, which we noted in the spectra. To this end, we first derived a mean out-of-eclipse spectrum disentangled with the program

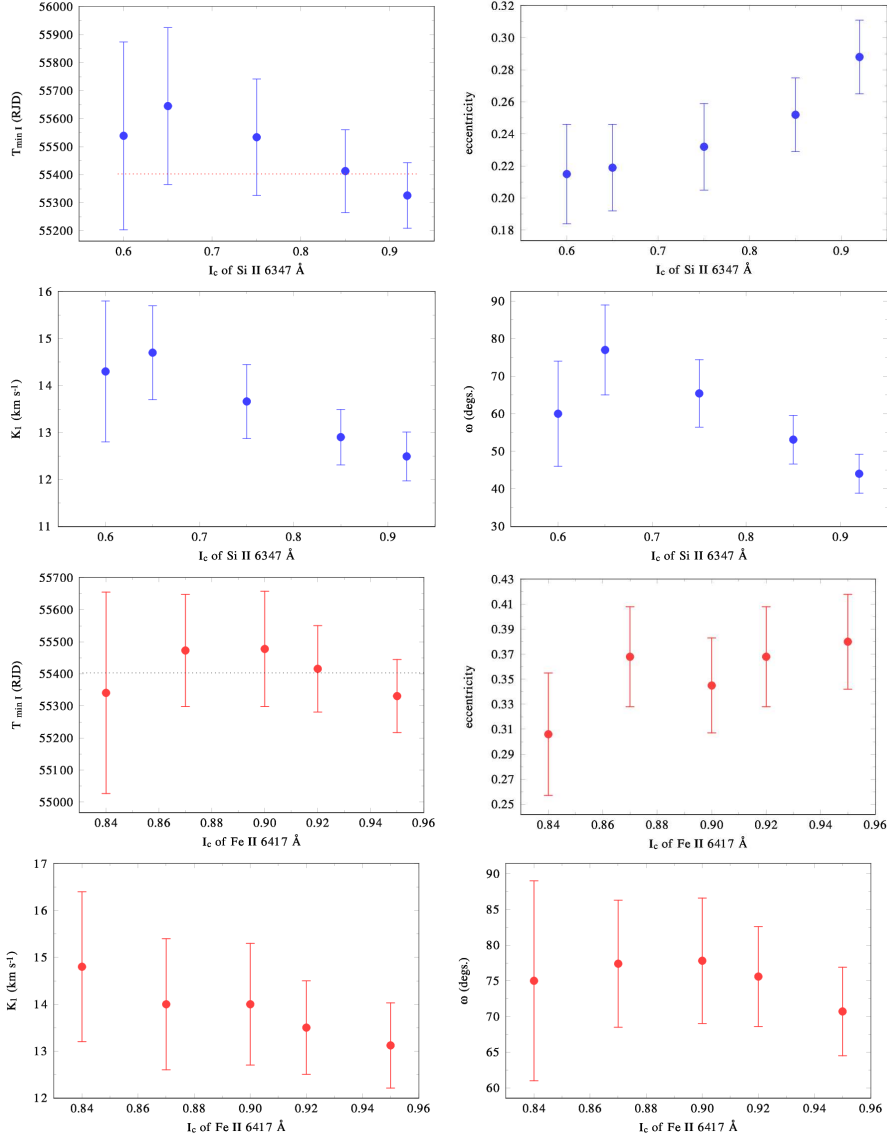


Figure 4: Evolution of orbital elements with the level, at which the bisector RV was measured. Top four panels: Si II 6347 Å, bottom four panels: Fe II 6417 Å.

KOREL (Hadrava, 2004b). Using the program SPEFO (Horn *et al.*, 1996; Škoda, 1996), we compared the disentangled line profiles with the individual observed spectra on the computer screen and recorded the needed RV shifts to

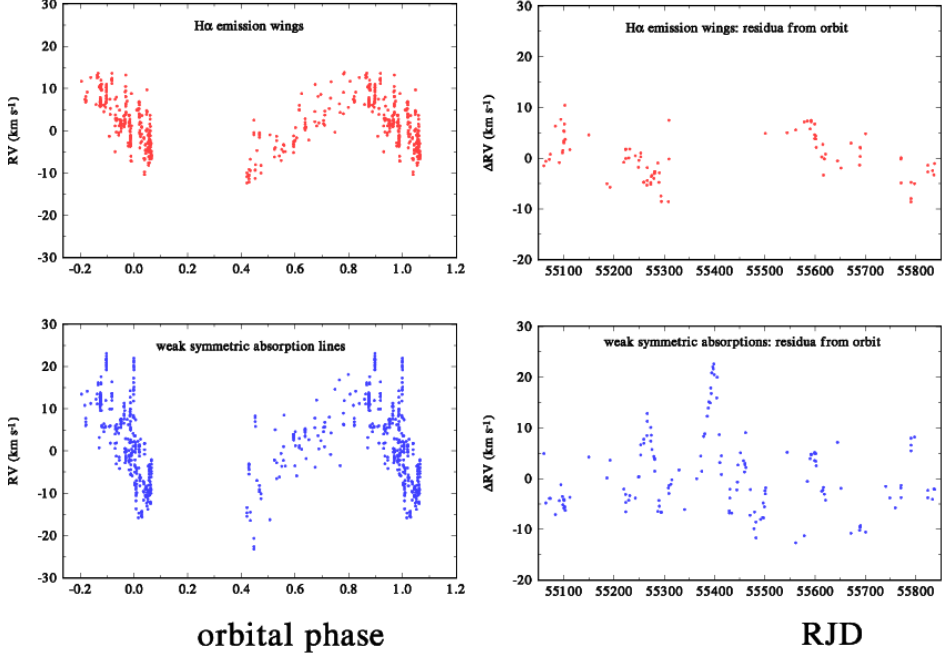


Figure 5: Left panels: RV curves based on the wings of the H α emission and on symmetric weak absorption lines. Right panels: The O-C deviations from the orbital solutions. See the text for details.

bring the profiles to overlap. In other words, we carried out something like a ‘manual cross-correlation’. The advantage of this tedious procedure is that one can avoid the telluric lines and flaws. Our result constitutes the final proof that the H α emission moves basically with the F primary. The orbital elements based on the wings of the H α emission and on the mean RV of weak symmetric absorptions are compared in Tab. I and the corresponding orbital RV curves and the $O-C$ residua from them are shown in Figure 5. Note the difference in the amplitude and shape of the curves as well as in the pattern of residual physical RV changes.

5. Light and colours changes

In Figure 6 we reproduce our light and colour curves of ε Aur. It is well seen that the physical light variations continued even during the whole eclipse. A very interesting new finding is the pronounced reddening of both colour indices near the third contact (RJD 55600), i.e. at the same time interval

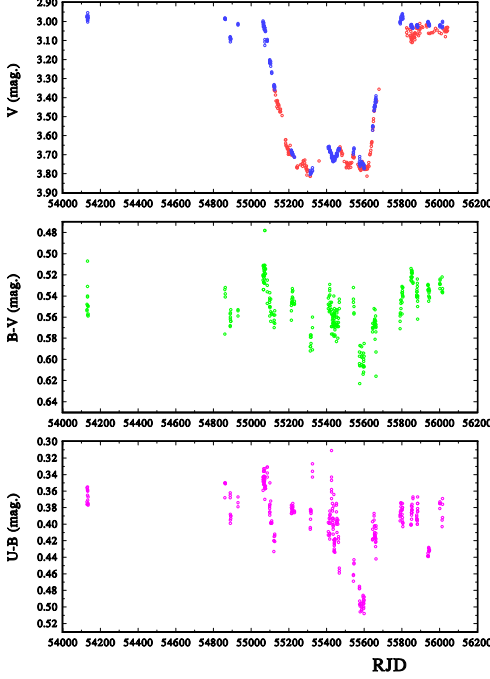


Figure 6: The V light curve and $B-V$ and $U-B$ colour changes during the last eclipse.

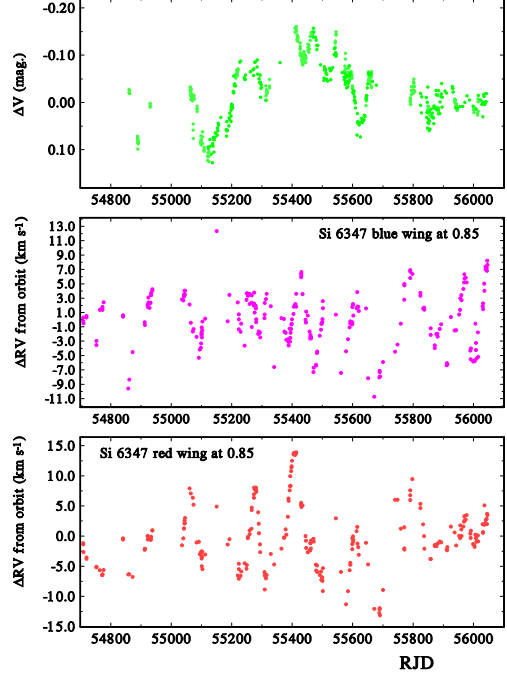


Figure 7: The $O-C$ deviations from the V light curve compared to the $O-C$ deviations from the locally measured RVs on the left and right wings of the Si II 6347 Å line.

when the extended blue-shifted contribution is seen in the Fe II 6417 Å absorption line (cf. Figure 3). In Figure 7 we compare the physical light variations in V (removing variations due to the eclipse) with the physical RV variations of local velocities measured at the blue and red wing of the Si II 6347 Å line at relative intensity 0.85 (removing the orbital changes). One can see that the variations at both line wings are usually in phase with each other but have different amplitudes, their correlation coefficient being 0.80. There might also be some correlation of local RVs with the light changes.

6. The dark disk: Ring-like structure or corotating inhomogeneities?

Leadbeater and Stencel (2010) argued that the excess EW of the K I absorption line during the eclipse varies in steps (see Figure 8, which is the

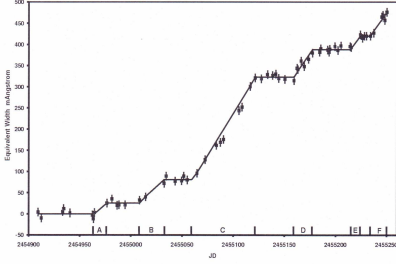


Figure 8: A reproduction of the plot of the equivalent width of the K I 7699 Å line from the paper by Leadbeater and Stencel (2010). The authors draw a step function and interpret it as evidence of a ring-like structure of the disk around the secondary.

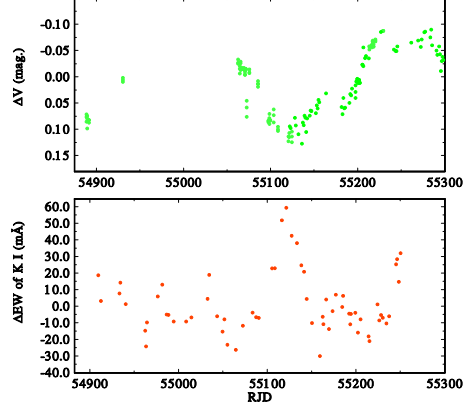


Figure 9: The $O-C$ from the K I equivalent width after detrending for a secular trend compared to the $O-C$ deviations from the eclipse light curve.

reproduction of their Figure 3 with a step function drawn) and elaborated on the idea by Ferluga (1990) that the disk might be actually a system of concentric rings reminiscent of Saturn’s rings.

We removed the trend from their EWs via spline functions and plot the $O-C$ deviations, comparing them with the V photometry residua (eclipse changes removed) from the same time interval in Figure 9. Both variations are *smooth* (*not in steps*), cyclic and probably mutually correlated. This might support the idea of corotating structures (spokes? resonantly excited density waves?) in the disk, instead of the suggested ring structure.

7. What we learned and how to interpret it?

- The $H\alpha$ emission moves in orbit with the F primary but with a smaller RV amplitude than that obtained from the absorption lines.
- The physical variations during the eclipse seem to be governed by two characteristic timescales (the first one already noted in some previous studies, e.g. Kim, 2008; Chadima *et al.*, 2011): cyclic changes on a time scale of 66 days and the travelling subfeatures moving from the blue to the red edge of the line profiles, which were found by us.
- Compelling evidence of extra circumstellar material projected against

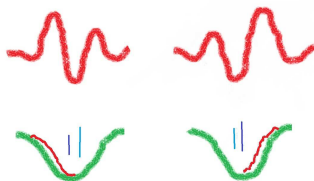


Figure 10: An illustration showing how the phase-locked V/R changes in a binary system can increase the true amplitude of the orbital RV changes of seemingly absorption lines, partly filled by a weak emission.

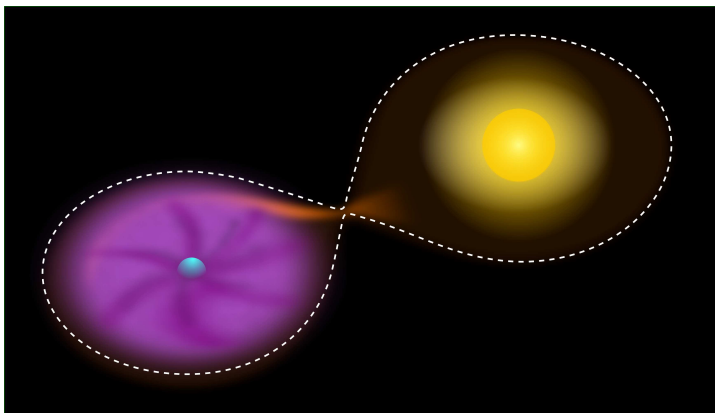


Figure 11: A cartoon of the system in our interpretation, showing the F supergiant with an $H\alpha$ emission-producing envelope, a cool disk around the B-type secondary with some corotating structures, and a gas stream flowing from the primary towards the disk. (Visualisation by David Ondřich.)

the primary near phases of the third contact around RJD 55600 is provided by a large reddening in the $U-B$ and $B-V$ indices, light decrease, and doubling of the Fe II 6417 Å line.

One can consider two possible explanations:

- Either the wings of the $H\alpha$ emission describe the orbital motion of the F star correctly and the higher RV amplitude of absorption lines is due to their slight filling by emission combined with the phase-locked V/R changes as illustrated in Figure 10 (see also Harmanec, 2003); we remind that the V peak of the emission is indeed statistically stronger prior to eclipse, when also orbital RV is more positive; or

- the optical centre of the H α emission is closer to the centre of gravity of the binary and the absorption-line RV amplitude describes the orbital motion of the F star better than that of the H α emission.

An idea which comes to mind is: What if the F primary is in the process of *episodic atmospheric mass transfer* each periastron passage via the Roche-lobe overflow? This is a situation known for some Be+X-ray binaries having eccentric orbits. Note that for ε Aur, the periastron passage occurs close to the primary mid-eclipse. Only the optically thin gas would be affected, the photosphere of the F star being safely detached. Appropriate modelling of such mass transfer should show whether this would be able to maintain the dense disk around the secondary.

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